5. Depth Sounding

5.1. Sounding Units

Depths shall be recorded in meters, with a precision of at least tenths of meters. Plotting units for final deliverables will be specified in the Hydrographic Survey Letter Instructions or Statement of Work.

5.2. Accuracy and Resolution Standards

5.2.1 Accuracy Standards

NOS standards for the accuracy of measured depths in hydrographic surveys apply to the systematic measurement of general water depths and to the least depths determined over wrecks and obstructions. By extension, they also apply to the elevations of rocks or other features which uncover at low water and to the measurement of overhead clearances. These standards apply regardless of the method of determination; whether by single beam echosounder, Multibeam echosounder, lead line or diver investigation.

The total sounding error in a measured depth at the 95 percent confidence level, after systematic and system specific errors have been removed, shall not exceed:

$$\pm\sqrt{[a^2 + (b \times d)^2]}$$

where a = 0.5 meters and represents the sum of all constant errors, (b * d) represents the sum of all depth dependent errors, b = 0.013 and is a factor of depth dependent error, and d is depth (in meters).

The maximum allowable error in measured depth includes all inaccuracies due to residual systematic and system specific instrument errors; the velocity of sound in water; static vessel draft; dynamic vessel draft; heave, roll, and pitch; and any other sources of error in the actual measurement process, including the errors associated with water level (tide) variations (both tidal measurement and zoning errors).

For Multibeam echosounders, the total sounding error is applicable to swath widths of at least two times the water depth (i.e., 45° to both sides of nadir). However, swath widths greater than two times the water depth may be used if the depth accuracy criteria stated above is met.

5.2.2. Multibeam Resolution Standards

The hydrographer shall maintain and operate the Multibeam sonar system, from data acquisition to processing, such that it detects shoals that measure 2 meters x 2 meters horizontally and 1 meter vertically in depths of 40 meters or less. For depths greater than 40 meters, the minimum size of detectable targets shall be 10 percent of the depth for horizontal dimensions and 5 percent of the depth for vertical dimensions. Depths shall be determined and recorded with a vertical resolution no coarser than 10 centimeters. The hydrographer shall ensure that vessel speed is adjusted so that no less than 3.2 beam footprints, center-to-center, fall within 3 m, or a distance equal to 10 percent of the depth, whichever is greater, in the along track direction.

Total swath width shall be no less than twice the water depth (i.e., 45E to both sides of nadir). The portions of the swath widths greater than twice the water depth that do not meet these resolution requirements and the accuracy requirements in Section 5.2.1 shall not be depicted on the preliminary smooth sheet or included in the digital file for the preliminary smooth sheet.

Sounding tracklines shall generally be parallel. Sinuous lines and data acquired during turns shall not be included in the final processed data, and shall not be used to meet coverage requirements.

5.3. Coverage

In general, there are two classifications of Multibeam coverage: Full Bottom Coverage and Set Line Spacing. The survey coverage technique will be specified in the Hydrographic Survey Letter Instructions or Statement of Work.

- ***Full Bottom Coverage***

Line spacing shall be such that the portions of the swaths that meet the accuracy and resolution requirements in Section 5.2 overlap to ensure that no gap in coverage exists due to the uncertainty in positioning and vessel motion.

- ***Set Line Spacing***

The hydrographer shall conduct Multibeam operations at the line spacing specified in the Hydrographic Survey Letter Instructions or Statement of Work.

5.3.1. Demonstration of Coverage

Regardless of coverage technique, the hydrographer shall demonstrate bottom coverage using a raster summary image, color coded by depth. The raster image shall be created from fully corrected data that meet accuracy and resolution specifications (see Section 5, Depth Soundings) are cleaned of all anomalous soundings, and serve as the source for all smooth sheet soundings. Each colored cell in the raster image shall be binned, line by line, using shoal biased filtering at a bin size not to exceed 5 meters + 5 percent of the depth.

5.4. Corrections to Echo Soundings

To meet the accuracy and resolution standards for measured depths specified in Section 5.2, observed echosounder depths must be corrected for all departures from true depths attributable to the method of sounding or to faults in the measuring apparatus.

In recognition of the possibility that some discrepancies in sounding may not be detected until the post-processing phase of the survey, the determination and application of corrections to echo soundings must be accomplished and documented in a systematic manner. In addition, all corrections shall be applied in such a way that the on-line values may be removed and replaced with a revised set of correctors in post-processing.
Corrections to echo soundings are divided into five categories, and listed below in the sequence in which they are applied:

- *Instrument error corrections* account for sources of error related to the sounding equipment itself.

- *Draft corrections* shall be added to the observed soundings to account for the depth of the echo-sounder transducer below the water surface.

- *Appropriate corrections for settlement and squat* shall be applied to soundings to correct the vertical displacement of the transducer, relative to its position at rest, when a vessel is underway.

- *Velocity of sound correctors* shall be applied to soundings to compensate for the fact that echo-sounders may only display depths based on an assumed sound velocity profile while the true velocity may vary in time and space.

- *Heave, roll, pitch, heading, and navigation timing error (latency) corrections* shall be applied to Multibeam soundings to correct the effect of vessel motion caused by waves and swells (heave, roll, pitch), the error in the vessel's heading, and the time delay from the moment the position is measured until the data is received by the data collection system (navigation timing error).

5.4.1. Instrument Error Corrections

In modern digital sounding instruments, instrument errors are generally small and of a fixed magnitude independent of the observed depth. Proper set up and adjustment of digital sounding equipment using internal checks and echo simulators will often eliminate instrument error entirely. However, to ensure the proper operation of echosounders, "confidence checks" shall be conducted periodically.

For single beam echosounders, a comparison should be made at least once per week with depths from bar checks, lead lines, or other single beam echosounders.

For Multibeam echosounders, comparisons should be made daily between the nadir (vertical) beam of the Multibeam and a single beam system.

Comparisons should be conducted during calm sea conditions, preferably in areas with a relatively flat sandy bottom. Any differences should be investigated, and if, after analysis, a corrector is necessary, it should be applied with an explanation of the cause of the difference.

5.4.2. Draft Corrections

The corrections for draft account for the depth of the transducer face below the surface of the water. Draft corrections comprise a value for the draft of the vessel at rest, sometimes known as static draft, and settlement and squat corrections which compensate for the variation in draft that occurs when the vessel is making way. The sum of the static draft and the settlement and squat correctors is known as the dynamic draft. Draft is transducer-specific. When more than one transducer is fixed to a vessel, the hydrographer must exercise care to apply the proper draft correction for each transducer.

- ***Static Draft***

The static draft, as an echo-sounding correction, refers to the depth of the transducer face below surface of the water when the vessel is not making way through the water. The required frequency of static draft measurements depends upon the range of variation in the vessel draft and the depths of water to be surveyed. For depths of 30 m or less, the static draft shall be observed and recorded to the nearest 0.1 m. Measurements are required with sufficient frequency to meet this criteria. When sounding in waters deeper than 30 m, the static draft shall be observed and recorded to the nearest 0.2 m.

Draft values for small vessels such as survey launches should be determined for the range of loading conditions anticipated during survey operations (maximum and minimum). Draft values for larger vessels must be observed and entered into the record before departing from and upon returning to port. In both cases, the draft should be determined by averaging the max/min or beginning/ending values if the differences do not exceed ±0.2 m. Otherwise, the applicable draft should be determined in 0.1 m increments. If significant changes to a vessel's draft (greater than ±0.1 m) occur, draft values shall be modified and applied accordingly.

C ***Settlement and Squat***

Transducers are generally displaced vertically, relative to their positions at rest, when a vessel is making way. Depth measurements are correspondingly affected by these vertical displacements. The displacements may be of sufficient magnitude to warrant compensation, especially when sounding at moderate to high speeds in shoal water. The factors accountable for this vertical displacement are called settlement and squat.

Settlement is the general difference between the elevation of a vessel when at rest and when making way. For lower speed, non-planing vessels, settlement is caused by a local depression of the water surface. Settlement is not an increase in the vessel displacement and, therefore, cannot be determined by reference to the water surface in the immediate vicinity. Vessels surveying at higher speeds may experience a negative settlement, or lift, when planing.

Squat refers to changes in trim of the vessel when making way and is generally manifested by a lowering of the stern and rise of the bow. Occasionally, the bow lowers on smaller vessels.

Major factors that influence settlement and squat are hull shape, speed, and depth of water beneath the vessel. Squat does not appreciably affect transducer depth on transducers mounted near amidships. Settlement, on the other hand, is almost always significant at normal sounding speeds, regardless of transducer location.

Combined effects of settlement and squat at the full range of sounding speeds must be determined to the nearest 0.05 m by the hydrographer at the beginning of the project for each vessel, including launches and skiffs used for hydrographic surveying in shoal or moderate depths. When the measurements are made, each vessel should carry an average load and have an average trim. Sounding vessel speeds (or RPM) must be entered in the hydrographic records during survey operations to permit accurate corrections for settlement and squat. If a Heave-Roll-Pitch (HRP) sensor is used to determine changes in squat, care must be taken to ensure that squat is not corrected for twice.

5.4.3. Velocity of Sound Corrections

C ***General***

To ensure that the overall depth measurement accuracy criteria specified in Section 5.2 are met, velocity of sound observations should be taken with sufficient frequency, density, and accuracy. The accuracy with which the speed of sound correction can be determined is a complex function of the accuracy with which salinity, temperature, and depth, or alternately, sound speed and depth, can be measured.

The velocity of sound through water shall be determined using instrumentation capable of producing sound velocity profiles with errors no greater than 2 meters per second. The sound velocity profile must reach the deepest depths of the survey but the physical measurement of sound velocity need only extend to:

- 95 percent of the anticipated water depth in 30 m or less of water. For example, if the maximum depth to be surveyed is 25 m, then the velocity profile should continue to a depth of at least 23.8 m.

C 90 percent of the anticipated water depth in depths from 30 m to 100 m.

C 85 percent of the anticipated water depth in greater than 100 m of water.

Sound velocity correctors must be determined accurately and often enough to ensure that the depth accuracy requirements in Section 5.2 are met. If changes in the temperature or salinity in the water column dictate that updated correctors are needed, additional sound velocity profiles shall be acquired. Additionally, the hydrographer should establish a means of monitoring changes in the water column between subsequent velocity casts.

Regardless of the sound velocity determination system employed, an independent sound velocity measurement system must be used to establish a confidence check. Confidence checks shall be conducted at least once per week. Include confidence check results in Separate III, Sound Velocity Profile Data (see Section 8.1.4.).

A geographic distribution of profiles may be necessary to correct for spatial and diurnal variability. Velocity corrections shall be based on the data obtained from the profile, and not based on an averaged sound velocity reading for the water column. Survey specific sound velocity information shall be included in Separate III, Sound Velocity Profile Data (see Section 8.1.4. Descriptive Report Supplemental Records).

The hydrographer shall calibrate sound velocity profiler(s) no earlier than six months prior to the commencement of survey operations. Calibration correctors shall be applied to all profiler data. These instrument(s) shall be re-calibrated at intervals no greater than twelve months until survey completion. In addition, the instrument(s) must be re-calibrated when the survey is complete if the completion date is later than six months from the date of last re-calibration. Copies of calibration data shall be included in Separate III, Sound Velocity Profile Data (see Section 8.1.4. Descriptive Report Supplemental Records**),** separates to be included with the survey data.

C *Velocity Corrections for Single Beam Surveys*

For each individual area identified, a minimum of at least one cast each week, taken in the waters surveyed that week, is required. The variation of physical conditions throughout a survey area or any portion thereof may dictate that this minimum may not be sufficient. Where casts taken early in a project indicate that physical characteristics are extremely variable, observations of velocity may be required more frequently.

C *Velocity Corrections for Multibeam Surveys*

The sound velocity profile must be known accurately in Multibeam swath sounding for two reasons. First, as in all echo-sounding, the depth is computed from the product of the velocity and the elapsed time between transmission of a sound pulse and reception of its echo. Second, since sound pulses travel at oblique angles through the water column, variations in the velocity profile will affect the path of sound through water. The sound path from the transducer to the bottom and back will affect not only the observed depth of water, but the apparent position of the observed sounding.

Even though sampling equipment and computer systems are capable of dividing the water column into intervals so small as to allow close approximation of the integral expression for harmonic mean velocity, practical limitations may require the hydrographer to use a small number of discrete points on the velocity profile for the purpose of correcting echo soundings. If the hydrographer chooses the inflection points of the smooth velocity profile as the discrete points for layer boundaries, the velocity curve between the points can reasonably

be approximated by a straight line. Integration of all the segments using the trapezoidal rule to approximate the area under each layer will yield very accurate results.

For multibeam operations, the following specifications apply to sound velocity profile frequency and application:

- One sound velocity profile shall be acquired immediately before the beginning of the data acquisition period. During the course of survey operations, changes in the water column should be monitored at a sufficient frequency such that the general requirements specified earlier in this section are met.

- Sound velocity profiles shall be acquired in the immediate area where subsequent data acquisition will occur.

- When using an undulating velocimeter, the real time sound velocity profiles shall extend to at least 80% of the anticipated water depth. At a minimum, one cast per 24-hour period shall extend to 95% of the anticipated water depth (30 m or less water depth).

5.4.4. Heave, Roll, Pitch, Heading, and Navigation Timing Error Corrections

Heave, roll, pitch, heading, and navigation timing error corrections shall be recorded in the data files and applied to all multibeam soundings and cross- track distances as applicable. For single-beam surveys, only heave shall apply.

- *Heave, roll, and pitch*. Heave shall be observed in no coarser than 0.05 m increments. Roll and pitch shall be observed in no coarser than 0.1 degree increments.

- *Heading* shall be observed in no coarser than 0.5 degree increments.

- *Navigation timing error* shall be observed in no coarser than 0.01 second increments.

5.4.5 Error Budget Analysis for Depths

The hydrographer shall discuss (in Section B2 of the Descriptive Report) the methods used to minimize the errors associated with the determination of depth (corrections to echo soundings). Error estimate ranges for six of these errors (measurement error, transducer draft error, settlement and squat error, sound velocity error, heave error and tide/water level error) are presented below. These errors are inherent to hydrographic surveying and all have practical minimums that are usually achievable only under ideal circumstances or with highly specialized equipment. In addition, some errors may be dependent on depth (e.g. sound velocity). Maximum allowable errors are specified to ensure that all errors sources are properly managed. It should be noted that if the maximum value for each error source is used in an error budget (i.e. root-sum-squared), the result will exceed the prescribed accuracy standard. The minimum and maximum values discussed below are at the 95% confidence level (i.e. 2 sigma).

Measurement error: This includes the instrument error for the sounding system, the effects of imperfectly measured roll/pitch and errors in detection of the sea floor due to varying density of the bottom material. Multibeam systems are particularly susceptible to this error due to the off-nadir nature of outer beams. The minimum achievable value is expected to be 0.20 meter at 10 meters depth. The maximum allowable error is 0.30 meter plus 0.5% of the depth.

Transducer draft error: This error is controlled by variability in vessel loading, and the techniques used to measure/monitor transducer draft. This error is depth independent with an expected minimum of 0.05 meter and an allowable maximum 0.15 meter.

Settlement and squat error: Conventional methods of determining settlement and squat are limited by sea surface roughness and proximity of a suitable location to the survey area. Careful application of modern methods (Real Time Kinematic GPS) will minimize this error. This error is also depth independent although the effect of settlement and squat is greater in shallow water. The practical expected minimum is 0.05 meter and the allowable maximum is 0.20 meter.

Sound velocity error: The factors associated with this error include (1) the ability to accurately measure sound velocity or calculate sound velocity from temperature, conductivity and pressure, (2) the spatial and temporal changes of sound velocity throughout the survey area and (3) how the sound velocity profile is used to convert measured time to depth. In addition, this error encompasses depth errors associated with refraction for Multibeam systems. The expected minimum is 0.20 meter and the allowable maximum is 0.30 meter plus 0.5% of the depth.

Heave error: This error is directly dependent on the sea state and the sensitivity of the heave sensor but is not dependent on depth. The expected minimum is 0.05 meter and the allowable maximum is 0.20 meter.

Tide/water level error: This error has been discussed in detail in Section 4. The practical minimum is 0.20 meter and the allowable maximum is 0.45 meter.

5.5. Quality Control

5.5.1. Multibeam Sonar Calibration

Prior to commencing survey operations, the hydrographer shall conduct a system accuracy test to quantify the accuracy, precision, and alignment of the Multibeam system. Testing shall include determination of residual biases in roll, pitch, heading, and navigation timing error. These values will be used to correct the initial alignment and calibrate the Multibeam system. System accuracy testing should be conducted in an area similar in bottom profile and composition to the survey area, and during relatively calm seas to limit excessive motions and ensure suitable bottom detection. In addition, system accuracy tests should be conducted in depths equivalent to the deepest depths in the survey area. Static transducer draft, settlement and squat corrections, sound velocity corrections, and tide corrections shall be determined and applied to the data prior to bias determination.

The order in which these biases are determined may affect the accurate calibration of the Multibeam system. The hydrographer should determine the biases in the following order: pitch, navigation timing error, roll heading. Variations from this order, or simultaneous determination of all values, must be explained and justified.

Pitch and navigation timing error biases should be determined from two or more pairs of reciprocal lines 500–1,000 m long, over a 10E–20E smooth slope, perpendicular to the depth curves. The lines should be run at different speeds, varied by up to 5 knots, for the purpose of delineating the along track profiles when assessing time delay. Navigation timing error bias could also be determined from running lines over a distinct feature (i.e., shoal) on the bottom, as long as the feature is pinged by the vertical (nadir) beam.

Roll bias should be determined from one or more pair of reciprocal lines 500–1000 m in length over a flat bottom. Lines should be run at a speed which will ensure significant forward overlap.

Heading bias should be determined from two or more adjacent pairs of reciprocal survey lines, made on each side of a submerged object or feature (i.e., shoal), in relatively shallow water. Features with sharp edges should be avoided. Adjacent swaths should overlap by 10–20 percent while covering the shoal. Lines should be run at a speed which will ensure significant forward overlap.

Once calibration data have been processed and final system biases determined, the new corrections shall be used in a performance check to ensure that the new system biases are adequate. The hydrographer shall discuss procedures and results in the Data Reduction section of the project Data Acquisition and Processing Report. Copies of all system alignment, accuracy, calibration reports, and performance checks shall be included in the Data Acquisition and Processing Report.

System accuracy testing shall be repeated whenever changes (e.g., sensor failure, replacement, re-installations, re-configurations, or upgrade; software changes which could potentially affect data quality) are made to the system's baseline configuration, or whenever assessment of the data indicates that system accuracies do not meet the requirements in Section 5.2.

5.5.2. Positioning System Confidence Checks

Confidence checks of the primary positioning system shall be conducted and recorded in the survey records at least once every week when USCG differential correctors are used as the primary positioning system, and once daily when non-USCG differential correctors are used. A successful confidence check shall compare positions from the primary system to simultaneously observed check positions from a separate, independent system with a positional accuracy better than 10 meters. The inverse distance shall not exceed 10 meters. If correctors for the primary positioning system are obtained from a non-USCG differential system, then the check system must use correctors from a reference station different from the primary system's. If correctors are obtained from a USCG differential station, the check system may use the same correctors as the primary system. The confidence checks shall be an integral part of the daily survey data record. Copies of positioning system confidence checks shall be included in the Vertical and Horizontal Control Report for each project.

5.5.3. Crosslines

C ***General***

The regular system of sounding lines shall be supplemented by a series of crosslines for verifying and evaluating the accuracy and reliability of surveyed depths and plotted locations. Crosslines shall be run across all planned sounding lines at angles of 45E to 90E. The preferred area in which to run crosslines is in an area of gently sloping bottom.

C ***Single beam***

The lineal nautical miles of crosslines for single-beam surveys shall be at least 8 percent of the lineal nautical miles of all planned sounding lines.

The hydrographer shall make a general evaluation of the single beam crossline to mainscheme agreement, and discuss the results in Section B of the Descriptive Report. If the magnitude of the discrepancy varies widely over the survey, the hydrographer shall make a quantitative evaluation of the disagreements area by area.

C ***Multibeam***

The lineal nautical miles of crosslines for Multibeam surveys shall be at least 5 percent of the lineal nautical miles of all planned sounding lines.

Comparisons shall be made between mainscheme lines and crosslines at 1% of all crossings (or 25 crossings, whichever is greater) distributed throughout the data both spatially and temporally. At these crossings the nadir or near-nadir depths of mainscheme lines shall be compared to each of the nearest unsmoothed soundings obtained from the crosslines. In addition, the nadir or near-nadir depths of the crosslines shall be compared to the nearest unsmoothed mainscheme soundings. The hydrographer shall perform a separate statistical analysis as a function of beam number for each of the mainscheme/crossline intersections used for comparison. Include a statement about the results in Section B of the Descriptive Report, and include a summary plot of each crossing in Separate V, Crossline Comparisons.

5.5.4 Multibeam Sun-Illuminated Digital Terrain Model (DTM) Images

Regardless of the Multibeam coverage technique used (see Section 5.3. Coverage), the hydrographer shall create two sun-illuminated DTM images. These sun-illuminated DTM images are the preferred method for detection of depth artifacts associated with errors in bottom detection algorithms, vessel motion compensation, navigation timing, water level correctors and false bottom detections.

Each image shall depict data illuminated from orthogonal directions, using a light source with an elevation no greater than 45 degrees. At a minimum, an 8 bit color depth shall be used for compilation of the sun-illuminated images. The two sun-illuminated images shall be created from fully corrected data that meet accuracy and resolution specifications (see Section 5, Depth Soundings) are cleaned of all anomalous soundings, and serve as the source for all smooth sheet soundings. Data shall be binned, line by line, using shoal biased filtering at a bin size not to exceed 5 meters + 5 percent of the depth.